2016 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)
Melbourne, Australia, Nov 28 - Dec 1, 2016

Microgrid Impact on Low Frequency Oscillation and Resonance in Power System

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Abstract—**Renewable technology based Micro Grid (MG) are mostly implemented with power electronic devices. Those MGs have no or very small aggregated physical inertia, depending on the generation technology used. Reduction in system inertia may have negative influence on stability of the system where the MG is integrated. Conversely power injection from MG might reduce line congestion, stress on synchronous generators and improve damping performance. In this paper, impact of MG penetration in a two-area power system is thoroughly investigated for small signal stability. Eigenvalues analysis shows that damping of inter-area and local modes enhanced as MG penetration increased. For variation in system operating conditions two neighboring eigenvalues coincided and interacted. Furthermore, a weak resonance phenomenon is detected. With increasing MG penetration, the detected resonance becomes weaker as the distance between two interacting modes was kept far enough. Eventually, the resonance can be prevented and system stability can be maintained with the help of MG.**

Keywords—Microgrid, small signal stability, damping, resonance

I. INTRODUCTION

One importance challenge in stand-alone distributed generation (DG) such as photovoltaic (PV) and wind energy conversion system (WECS) is how to maintain a stable operation due to renewable energy sources (RES) uncertainties. This leads to the necessity to coordinate such clusters of DG units to form a single controlled and supervised power system, which may even have the capability to operate both in islanding and in parallel with the existing grid, called microgrid (MG).

Although MG provides more reliable supply and seamless integration of RES, grid connected operation of MG brings some challenges to the grid stability. Conventionally, synchronous generators are responsible to provide inertia for maintaining stable operation of power system after being subjected to small and large disturbances. Replacing a certain portion of generated power from synchronous generator with MG introduce deviation in system inertia which highly correlated to dynamic response and restoring mechanism of the affected generators [1].

Most of the DG units in a MG employed power electronic for interfacing and power conversion. Converter based PV system has negligible physical inertia. While, in variable speed WECS, such as doubly fed induction generator (DFIG) and fully rated converter wind power plants, implementation of asynchronous generators and converter system introduce different dynamic from those of synchronous machine. As a result, integrating wind power to the grid significantly change the grid operation. DFIG might either improve or worsen the damping of critical eigenvalues as presented in [1, 2]. Furthermore, in [3, 4], it was pronounced that high penetration of wind power clearly improved the inter-area modes. It was also investigated in [5] that even wind power plant did not worsen the damping of inter-area modes, the change in system operating points might reduce damping of the these modes. Improvement of oscillatory modes due to PV integration and WECS in distribution system was investigated in [6]. It was also monitored that impact of PV on small signal stability varies with the change of system operating condition [7, 8] .

Advanced MG architecture and control system was required to make sure stable operation while it was integrated to power system. On the other hand, the complexcity design of MG exhibit more nonlinear effect and dynamic modal behaviour [9]. When two eigenvalues were located closely, the interaction of neighboring modes potentially influence the power system oscillatory behaviour. Specifically, those eigenvalues might come closer, interact and coincide both in damping and frequency. Around the coinciding point, the corresponded modes become highly sensitive to parameter variations. This phenomenon is then defined as a resonance. Depending on the closeness of the modes, it can be catergorized as Weak or Strong Resonnance. Near a strong resonance, trajectories of affected modes change significantly, result in more oscillatory condition and become a precursor to the system instability [10, 11].

Initial research regarding influence of MG on low frequency oscillatory modes was presented in [12]. More practical scenario considering distribution lines and hybrid RES based DG units in MG has been addressed in this paper. Moreover, correlation between resonance event and small signal stability performance has been further investigated. Comprehensive MG model have been developed in DigSilent Power Factory analytical software. Furthermore, small signal

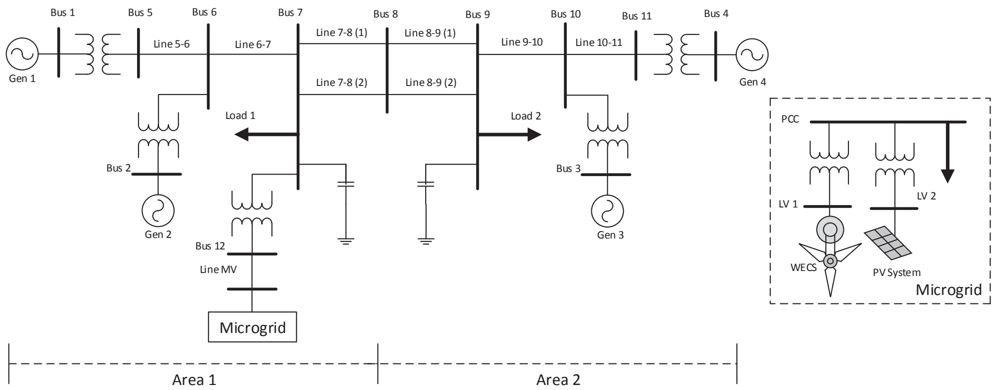


Fig. 1. Two-Area Four Generators System with Microgrid.

stability performance of the system was analysed and validated through eigenvalues and time domain simulation.

The remainder of the paper is organized as follows. A system modelling of two-area power system and PV-Wind, MG involving their controllers for small signal investigation is presented in Section II. Section III describes analytical procedure for small signal stability and resonance. The simulation results in detail ae presented and discussed in Section IV. Conclusions and contributions of this paper are highlighted in Section V.

II. Model Development

Single line diagram of two areas four generators system is shown in Fig. 1. Dynamic parameters of the studied system are obtained from [13]. In steady state condition without MG penetration, 400 MW is imported from Area 1 to Area 2 through parallel long transmission lines. Synchronous generator equipped with governor and type 1 IEEE excitation system are modeled in the small signal stability analyses.

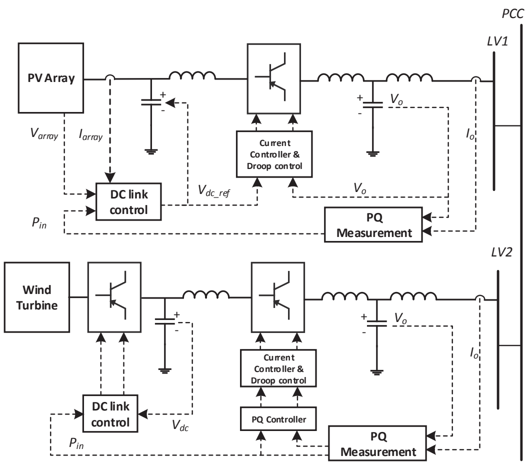


Fig. 2. Microgrid Control Strategy.

To investigate impact of MG on small signal stability, particularly on low frequency oscillation and resonance in power system, hybrid MG system comprising of fully rated WECS and PV system as proposed in [12] are connected to bus 7. In grid connected mode of operation, MG provide additional power for supporting load demand in the existing system. Regulation of active and reactive power form each DG units in MG is realized by control scheme as shown in Fig. 2. In this control algorithm, DC link control is responsible to maintain stable condition of input voltage hence it will ensure stable operation for inverter. Current controller loop generate control signal for grid side inverter hence output power regulation from MG can be achieved. In this paper, DigSilent Power Factory generic model of PV and fully rated WECS have been implemented. More practical condition of MG operation is then approached by connecting local load with 5 MW capacity and distribution line to the proposed MG model.

III. Small Signal Stability and Resonance in Power System

A. Small Signal Stability

Small perturbation such as small load change and system parameters variation deviates operating point of the power system. Following the disturbance, unbalance condition between mechanical and electromagnetic torque comprising of synchronizing and damping torque might be occurred. Small signal instability leading to oscillatory with increasing amplitude in rotor will emerge due to insufficient damping torque. This eventually leads to the system instability. Stability performance during disturbance is characterized by eigenvalues of system state matrix. Investigation of small signal stability is conducted through modal analysis since change in operating point is reflected in the change of eigenvalues.

The proposed study investigate how increased MG penetration level affected system small signal stability particularly on low frequency oscillation in the range of 0.1-2 Hz focusing on local and inter-area modes. System stability performance is reflected in trajectories of eigenvalues. Furthermore, complex eigenvalues indicate frequency of oscillation (*f*) and damping ratio (ζ) of the modes, which can be stated as given in (2) and (3).

$$\lambda_i = \sigma_i \pm j\omega_i \tag{1}$$

$$f_i = \frac{\omega_i}{2\pi} \tag{2}$$

$$\zeta = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{3}$$

Correlation between state variables and the sensitive modes is obtained by conducting participation factor analysis. The participation factor of *i*-th state variables and the *j*-th modes is given by

$$p_{ij} = \phi_{ij}\psi_{ij} \quad (4)$$

Where ϕ_{ij} and ψ_{ij} respectively represent the element on the right eigenvector and left eigenvector.

B. Resonance in Power System

Resonance from small signals stability point of view might be defined as coincidence of two eigenvalues in real axis or in both frequency and damping for real and complex modes respectively. Classification of Strong and Weak resonances correspond to whether linearization is not diagonalizable or diagonalizable [10]. If the linearization is not diagonalizable at the resonance, it called as a Strong resonance, otherwise it is a Weak resonance. Near a Strong resonance, the involved eigenvalues are very sensitive to parameter variation. Furthermore, trajectories of approaching eigenvalues change their direction drastically, even one mode moves toward right half of complex plane and become unstable [10].

Interaction of modes near a Weak resonance is much less significant than in a Strong resonance. Weak resonance phenomenon might be emerged in power system with special configuration [10]. Possible configurations for emerging weak resonance are decoupled or symmetric power system. Local eigenvalues corresponded to one area potentially coincide with local modes from different area during a parameter variation. Near a Weak resonance, the direction of eigenvalues is not change drastically. Weak resonance affect the damping performance of the corresponded modes and if the effect is strong enough, this can lead the system into oscillatory instability [11].

Resonance phenomenon could occur in power system due to perturbation on machine inertia, increasing loading in tie line and variation of power system control parameters. Dobson et.al in [9-11] investigated Strong and Weak resonance in inter area power system. In 3 and 9 bus test systems, Strong resonance emerged and lead to the system instability due to change of generated power from generators. Furthermore, similar references also observed that Weak resonance between two local modes may present in two area power system. This happened due to perturbation of reference voltage and generator damping constant in assumption that those structure of power system is decoupled each other.

IV. Result and Discussion

Two-area power system with MG connected to bus 7 is investigated in this work as shown in Fig. 1. Simulations were performed to observe impact of increased MG penetration on small signal stability. Focus of discussion in this paper is emphasized on low oscillatory frequency modes in the range of 0.1 to 2 Hz, which corresponded to local and inter-area electromechanical modes from synchronous generator. MG penetration level was increased gradually from 10 MW to 50 MW and trajectories of the sensitive modes were observed. Additional local load of 5 MW and distribution lines were modelled to realize more practical configuration of MG integration.

It is also expected that MG integration affect the interaction among sensitive eigenvalues. In this paper, active power from generator 1 was reduced from 700 MW to 400 MW hence most of the active power from area 1 was generated by generator 2. Voltage reference of generator 2 was then varied from 1.0 pu to 1.05 pu to give more opportunity of having resonance in the observed system.

A. MG impact on Small Signal Stability

Table I represents local and inter area modes in base case condition without MG penetration. Local modes 1 and 2 respectively represent oscillatory eigenvalues among generators in the similar area. Participation factor analysis shows that local modes 1 corresponded to rotor angle (δ_1, δ_2) and speed (ω_1, ω_2) of G1 and G2. While local modes 2 correlated to rotor angle (δ_3, δ_4) and speed (ω_3, ω_4) of G3 and G4. Inter-area modes indicated oscillatory condition between generators in different area. The inter-area modes correspond to rotor angle and speed of G1 to G4. From table I, it is clearly seen that damping ratio of local modes in area 1 and 2 (8.13% and 8.82% respectively) are much higher than inter area modes (1.54%). This means that possibility of local modes instability due to small disturbance is much lower.

TABLE I. LOCAL AND INTER AREA MODES IN BASE CASE CONDITION

Modes	Real (1/s)	Imaginary (rad/s)	Damping Ratio (%)	Frequency (Hz)
Local 1	-0.767	9.39	8.13	1.49
Local 2	-0.835	9.55	8.71	1.53
Inter Area	-0.042	3.64	1.54	0.57

As MG penetration at bus 7 increased gradually from 10 to 50 MW, trajectories of sensitive modes varied along left hand side of complex plane. There are two possible impact of integrating MG to the power system. Replacing a certain portion of generated power from synchronous generator reduced the aggregated physical inertia of the entire system, deteriorated damping performance and may alter the critical low frequency modes. On the other hand, increased MG penetration level potentially enhanced the system stability due to reduction of generator stress, congestion and power loss along the distribution and transmission line.

Table II presents the detailed analysis of the local modes for all considered MG penetration level. Since MG was connected at bus 7, the damping performance of local modes in area 1 improved, indicated by enhancement of damping ratio of the corresponded modes from 8.25% to 8.52%. While, local modes of area 2 relatively fixed at their position as MG penetration increased. The long distance between MG at bus 7 and area 2 potentially reduced the impact of MG on area 2. It was also observed that frequency of oscillations in both local modes were relatively unchanged as power injection from MG increased.

More significant effect of increased MG penetration level was experienced by inter-area modes as presented in Table III.

The eigenvalues analysis showed that damping performance of the inter-area modes enhanced from 1.54% in base case scenarios without MG to 1.67% with 50 MW power from MG. Similar to the result in trajectories of local modes, oscillatory frequency of the inter area modes appeared unchanged at 3.7 rad/s or 0.58 Hz. The change of MG penetration level may not improve the small signal stability of the investigated modes drastically due to small amount of the injected active power compared to the entire load capacity of the existing system (only 2% from the total load demand). Moreover, from previous research, it was also pronounced that MG output levels do not have a direct contribution on the modes of the system [3].

TABLE II. LOCAL MODES AFFECTED BY MG PENETRATION

MG (MW)	Local Modes Area 1			Local Modes Area 2		
	Re. (1/s)	Im. (rad/s)	Damp. (%)	Re. (1/s)	Im. (rad/s)	Damp. (%)
10	-0.778	9.39	8.25	-0.835	9.54	8.70
20	-0.786	9.38	8.34	-0.834	9.54	8.71
30	-0.793	9.38	8.43	-0.835	9.55	8.70
40	-0.802	9.38	8.52	-0.834	9.55	8.70
50	-0.806	9.39	8.56	-0.834	9.56	8.69

TABLE II. INTER AREA MODES AFFECTED BY MG PENETRATION

MG (MW)	Inter Area Modes		
	Real (1/s)	Imaginary (rad/s)	Damping (%)
10	-0.057	3.642	1.55
20	-0.060	3.691	1.63
30	-0.061	3.691	1.64
40	-0.061	3.691	1.65
50	-0.062	3.692	1.67

Verification of previous eigenvalues analysis can be conducted through time domain simulation. To excite the investigated modes with low damping characteristic, large disturbance was applied to the system. A three-phase fault was applied to bus 7 and cleared after 150ms. Comparisons of system dynamics response in base case condition and with MG penetration (20 MW and 50 MW) were observed. Fig. 3 represents transient response of the generator 2 and 4 speed due to applied disturbance. It was observed that MG brought advantages to the system response. MG provided additional damping during fault hence the amplitude of oscillation was lower compared to the condition without MG. Furthermore, since MG was connected to bus 7, it was far from generator 4. Hence, the effect of additional damping from MG in area 2 was less significant than in area 1, indicated by higher oscillation during disturbance.

Fig.4 depicts time response of generator rotor angle during fault condition at bus 7. Generator rotor angle in area 2 adversely impacted by the fault and need longer time to settle down. While, more stable condition during transient time was experienced by generator 1, indicated by short oscillation of the rotor angle. From time domain simulation it was also monitored that inter-area modes had more influence to the transient response of the generators. The local modes which had much higher oscillatory frequency and damping ratio than inter-area modes damped very fast hence only frequency from inter-area modes emerged. It was visualized on dynamic response of generator speed at fig. 2, 3 and 4 with frequency around 0.5 Hz. Time domain simulation also suggested that the proximity of the generator units to the MG is a notable factor to enhance the small signal stability.

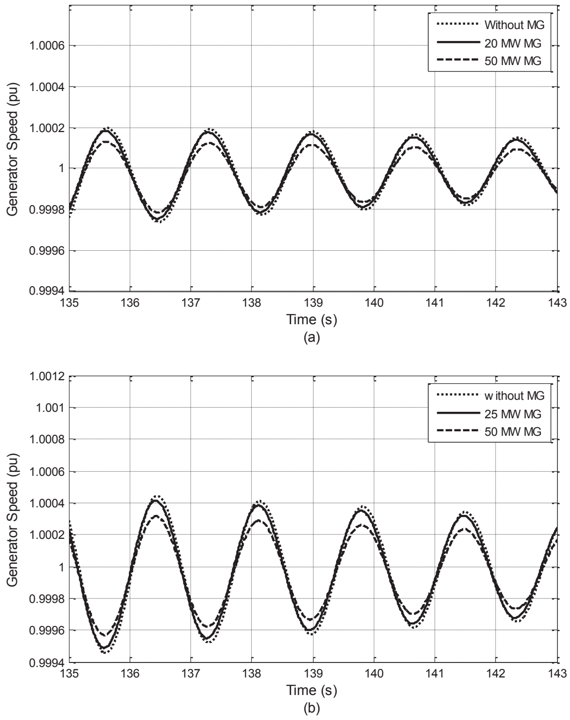


Fig. 3. Speed of generator 2 (a) and 4 (b) for three phase fault at bus 7.

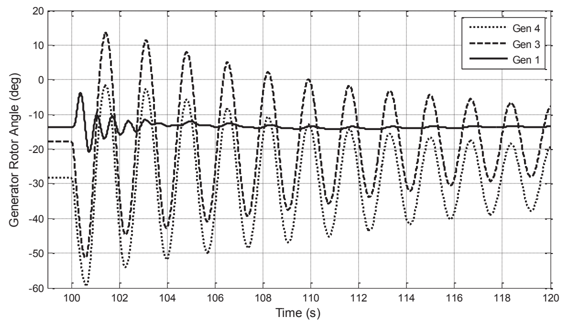
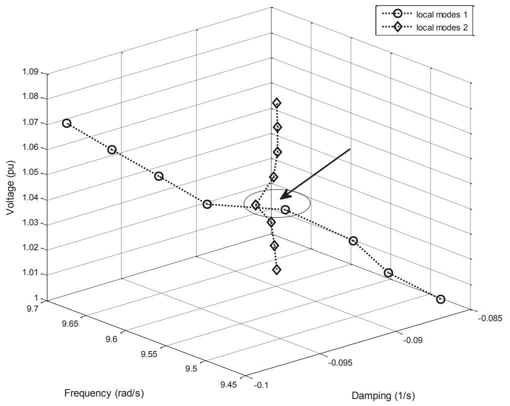


Fig. 4. Rotor angle of generator 1, 3 and 4 for three phase fault at bus 7.

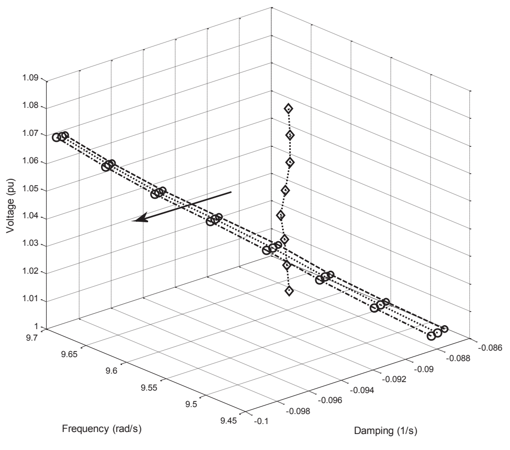
B. Resonance in Two Area System

From small signal stability point of view, as parameter varied and perturbation took place, the eigenvalues of the state matrix will vary. Among the modes variation, two eigenvalues may approach each other and coincide both in frequency and damping which generally called as resonance. Commonly, strong resonance is rarely occurred since it required exact coincide of the interacting eigenvalues. However, near a Strong resonance, two modes may interact each other and become extremely sensitive to the parameter variation. The direction of eigenvalues trajectories can change drastically even toward to the right half plane, result in system instability.

In two-area power system, interaction between modes potentially emerged between local modes in area 1 and area 2 since they almost had similar frequency and damping ratio as presented in Table I. Reference voltage of generator 2 will be varied from 1.0 to 1.05 to realize the parameter variation scenarios. Trajectories of two local modes were evaluated to find out resonance event. Fig. 5 depicts the trajectories of local modes in area 1 and area 2 during variation of voltage reference in generator 2. Without MG penetration, weak resonance phenomenon was experienced by local modes as depicted in Fig.5a. At 1.03 pu, as marked by a circle, two local modes were approaching and nearly coinciding at the frequency of 9.53 rad/s. The obtained result was consistent to the previous result in [11]. It was monitored that when two eigenvalues were initially approaching each other in frequency, after the resonance point, the damping performance of the investigated modes will separate quickly. Beyond this point, damping of local modes in area 1 significantly improved. Conversely, small signal stability performance of local modes in area 2 deteriorated, indicated by decrease of damping ratio of the corresponded modes.



(a)



(b)

Fig. 5. Local modes trajectories near weak resonance without (a) and with (b) MG penetration.

Integrating MG to the system bring beneficial effect not only for small signal stability but also for resonance phenomenon. Fig.5b depicts the influence of increased MG penetration on power system resonance. Three power injection levels from MG, 10 MW, 30 MW and 50 MW were investigated. With MG connected to the system, two local eigenvalues did not approach each other as near as in the case without MG penetration. As MG penetration level increased, the trajectories of modes from area 2 were relatively unchanged. While local modes of area 1 shifted away from modes 2. Since the distance between two investigated modes increased, only small interaction was experienced. Moreover, the effect of the resonance between two modes did not emerge. Resonance prevention due to MG integration may improve system small signal stability. The critical modes became less sensitive to small perturbation and parameter variation hence systems stability can be maintained. The position of two local modes near a resonance point with 1.03pu reference voltage from generator 2 is presented in Table IV.

TABLE IV. LOCAL MODES NEAR RESONANCE POINT WITH MG PENETRATION

MG (MW)	Local Modes Area 1			Local Modes Area 2		
	Re. (1/s)	Im. (rad/s)	Damp. (%)	Re. (1/s)	Im. (rad/s)	Damp. (%)
0	-0.843	9.493	8.85	-0.846	9.54	8.83
10	-0.857	9.497	8.98	-0.843	9.54	8.87
30	-0.862	9.499	9.05	-0.842	9.55	8.78
50	-0.881	9.509	9.23	-0.841	9.56	8.77

Participation factor analysis confirmed the interaction of the local modes near the resonance point. Without MG connceted to the system and far from resonance point, primarily, local modes only correlated to the state variables in the same area and state variables from other area did not participate in the corresponded modes. Around a resonance point, however, state variables from different area may also participated. This represent interaction between local modes near a resonance. Fig.6 shows participation factor analysis of local modes in base case scenario without MG far and near from a resonance point. Near resonance, state variables from different area also participate in local modes. State variables of G4 rotor angle participated on local modes 1 while G1 speed and rotor angle also contribute on local modes 2. This indicated interaction between two local modes around resonance point.

In Fig.5b, as MG penetration level increased, the interaction of local modes around resonance was weaken. The distance between two local modes became further hence the direction of participated modes did not change significantly. The presented result was strengthen by following participation factor analysis in Fig.7 which shows the participation factor analysis of local modes in area 1 (a) and local modes area two (b) near a resonance point with variation of MG penetration level. From this figure, it was monitored that participation factor of G4 and G1 state variables in local modes area 1 and area 2 respectively, it was observed that as MG power injection increased, the damping performance of modes from area 1 improved while local modes of area 2 relatively was fixed at its initial condition.

Improvement of damping in mode 1 results in motion of corresponded modes toward open left half of complex plane. Hence, the distance of two local modes become further. As a result interaction as an effect of resonance phenomenon became weaker. It was suggested, since MG provides beneficial impact of system damping, it also contributes to prevent possibility of weak resonance in power system. Eventually the damping performance during small disturbance improved and system small signal stability can be maintained.

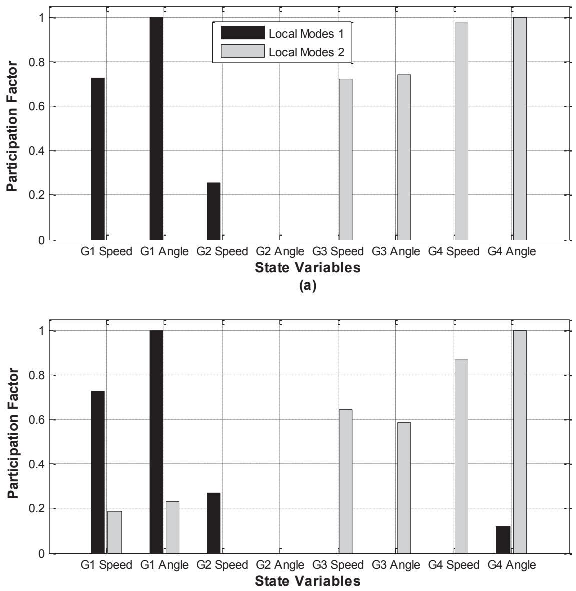


Fig. 6. Local modes participation factor in base case scenario far (a) and near (b) weak resonance.

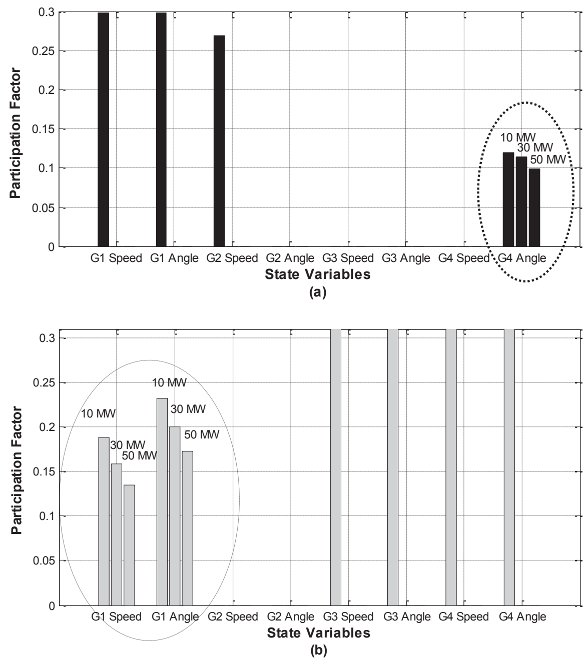


Fig. 7. Local modes 1 (a) and 2 (b) participation factor near weak resonance with increased MG penetration.

V. CONCLUSION

Influence of MG penetration particularly on small signal stability and resonance of power system was presented. The work shown that damping performance and system small signal stability during disturbance enhanced as MG penetration increased. The monitored result also suggested that proximity of MG connecting point to the generator was an important factor to improve stability. It was further validated by time domain simulation.

From the presented work, it was also observed that re-dispatching and small variation of generator parameters potentially lead to resonance phenomenon in existing system. Interaction of two local modes emerged resonance phenomenon. Near a resonance point, the direction of investigated modes change significantly. In this paper, MG contributed to prevent resonance since improvement was experienced by local modes from area 1. Furthermore, the distance between two interacting modes was maintained. Eventually, the resonance can be avoided.

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